Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences
Pacific Region
Canadian Science Advisory Secretariat
Science Response 2012/045

TRANSPORT OF JAPAN TSUNAMI MARINE DEBRIS TO THE COAST OF BRITISH COLUMBIA: AN UPDATED REVIEW

Context

On December 9, 2011, Fisheries and Oceans Canada's (DFO) Ocean Sciences Division (OSD) in Pacific Region requested that DFO Science, Pacific Region, provide information and advice regarding the transport of debris to the west coast of Canada from the March 2011 earthquake and tsunami in Japan. This request arose because OSD has received multiple requests from other federal government departments and agencies, the Province of British Columbia, and the media for information on the timing, location and quantity of debris generated by the earthquake and tsunami that might reach Canadian waters and shorelines.

In response, a Science Special Response Process (SSRP) was conducted on March 6 2012 based on existing information on the debris, including results from two independent ocean circulation models simulating debris transport in the North Pacific Ocean. The results of this SSRP are available here: http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_006-eng.pdf. It included responses to the following questions that were put to OSD:

1. **When and where is debris from the 2011 Tōhoku tsunami expected to reach Canadian waters and shorelines?**
2. **What types of material are expected in the debris and what is the estimated quantity of material likely to enter Canadian waters and/or reach shorelines?**
3. **What monitoring of the debris is occurring while it drifts at sea from a Canadian/international perspective?**
4. **What risks, if any, does this debris pose for species, habitats, and ecosystems in Canadian waters? and,**
5. **What are the potential navigational impacts in Canadian waters?**

The present report represents an update on the original SSRP which it now supersedes. This update is necessary due to several developments that have taken place since the original document was prepared. It was recognized in the original report that an update to the advice provided would be likely required as new information became available. Recent developments include observations of tsunami debris at sea, and the arrival of significant pieces of debris along the west coast of North America. Complementing these events, new model simulations have been made public. Whereas the simulations that were available previously were for objects with essentially zero windage, the new simulations examine the influence of windage on the transport of debris. In addition, rather than climatological statistics, the new model runs make use of the actual wind forcing over the Pacific from March 2011 through August 2012.

The questions considered in this update are as given above, and unchanged from those of the original SSRP. The following are the updated responses/conclusions given in response to these questions:

1. **When and where is debris from the 2011 Tōhoku tsunami expected to reach Canadian waters and shorelines?** Here it is necessary here to make a distinction based on the windage of the debris. Large objects that float well above the water and are subject to direct

forcing by the wind have already arrived in Canadian waters and washed up on the shores of British Columbia. Model simulations show that such high windage debris started to arrive along the BC coast during the winter of 2011-12. Most of the debris, however, is thought to consist of objects with low to moderate windage. Based on model simulations, such debris from the Japan tsunami is transported more slowly and expected to approach the coast of North America during the second half of 2012, through the first half of 2013. Debris will likely continue to arrive at the coast over a large spatial area from Alaska to northern California for several years. Most of this debris will consist of small pieces rather than large objects owing to the effects of surface currents, winds, and waves. It is important to note that the debris generated by the tsunami will be in addition to the existing debris load floating into Canadian waters and washing ashore in British Columbia every day. Existing patterns of debris deposition on shorelines are not expected to change when debris from the tsunami begins arriving. Since the origin of the most debris washing ashore is not identifiable, the only indicator of tsunami debris may be an increase in the quantity of debris (by weight) washing ashore relative to the long-term average. It is unlikely that debris from the tsunami will enter the Strait of Georgia due to seaward flowing near-surface currents at the mouth of Juan de Fuca Strait and the barrier presented by the Gulf and San Juan Islands.

2. **What types of material are expected in the debris and what is the estimated quantity of material likely to enter Canadian waters and/or reach shorelines?** Both the quantity and composition of tsunami debris expected to reach North America are highly uncertain. Initial estimates of the mass of debris swept into the ocean ranged between 20 and 25 million tonnes. However, an updated estimate from the Government of Japan is that about 1.5 million tonnes of tsunami-generated debris remains afloat as of March 2012. While the composition of the debris is not known in detail, the Government of Japan estimates that the preponderance of the debris is construction material from houses that were swept to sea. As a result, it is thought that lumber, which is used extensively in Japanese buildings, represents an important component of the debris. Individual pieces of debris will vary enormously in size and weight, with the largest weighing hundreds of tonnes or more. The vast majority of objects are likely to be very much smaller. Based on existing knowledge of oceanographic processes and marine debris transport, only the most buoyant and durable objects will survive the trans-Pacific crossing and reach North America. Models used to forecast debris movements show that most of the low windage tsunami debris will remain in the ocean for many years and collect within an area of the Sub-tropical Convergence Zone referred to colloquially as the "North Pacific Garbage Patch". It is unlikely that debris caught in the Garbage Patch will subsequently reach the coast of British Columbia.

3. **What monitoring of the debris is occurring while it drifts at sea from a Canadian/international perspective?** Debris swept into the Pacific Ocean was tracked by an environmental monitoring satellite for about one month after the tsunami. Attempts to locate debris with higher resolution satellite imagery are ongoing, but are limited to small patches of the ocean. In the absence of systematic monitoring of debris by satellites, opportunistic sightings by passing vessels were compiled and catalogued by the Government of Japan up to November 2011. Presently, the National Atmospheric and Oceanic Administration (NOAA) of the U.S. Dept. of Commerce is engaged in an ongoing effort to compile sightings of tsunami debris.

4. **What risks, if any, does this debris pose for species, habitats, and ecosystems in Canadian waters?** It is impossible to quantify the risk to marine species, habitats or ecosystems in British Columbia associated with tsunami debris and whether this risk surpasses any thresholds for effects. The baseline risks to marine habitats, species and ecosystems in Canadian waters from the existing marine debris load are poorly understood and documented and as a result the expected incremental increase in risks associated with

the arrival of tsunami debris cannot be estimated at present. The potential does exist for the tsunami debris to act as a vector for the transfer of invasive species to the coastal waters of British Columbia. On the other hand, the risks from radioactivity on the debris associated with ^{131}I and ^{137}Cs originating from the Fukushima nuclear plant are believed to be low. Limited testing of tsunami debris have found that radioactivity levels were below detection limits.

5. **What are the potential navigational impacts in Canadian waters?** Navigational impacts in Canadian waters associated with marine debris are poorly known. The highest risk to navigation is likely related to large objects arriving in coastal waters or in shipping lanes, particular if they are floating mostly below the water line and thus largely invisible to ship's radar and crews. This may include objects such as partially submerged vessels, shipping containers, docks, etc. The probability of houses surviving a trans-Pacific crossing intact is believed to be very low. Although drifting nets, ropes and other entangling debris from the tsunami pose a risk, this risk and the resulting impacts are likely incremental increases on the current navigational risks associated with entangling debris. Small objects (e.g., logs or small pieces of wood) are not believed to pose any additional risk to vessel traffic off the west coast of Vancouver Island.

This Science Response report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, Regional Science Special Response Process (SSRP) of November 5, 2012 on the Transport of Marine Debris from the 2011 Tōhoku Tsunami to the west coast of Canada.

Background

The magnitude 9.0 mega-thrust earthquake that occurred under the ocean about 70 km off the east coast of Japan on 11 March 2011 generated a tsunami that caused widespread destruction and loss of life in Japan. The tsunami inundated low lying coastal areas of the Tōhoku region of northeast Honshu Island and, in several instances, entire villages were swept away by the surging waters. A large quantity of debris was produced by the tsunami, much of which was swept into the ocean by the retreating waters. This marine debris is presently being transported and dispersed by ocean currents. Notable pieces of debris have already entered Canadian waters. In the months and years to come it is expected that more debris will find its way to the shores of British Columbia. The following report provides a brief overview of present state of knowledge regarding the transport of marine debris from the Tōhoku tsunami.

Analysis

Marine debris

The debris that was swept to sea by the tsunami is composed of a very wide variety of objects of different materials and sizes, some as large as entire houses. The actual mass or volume of this material is not known accurately. The Ministry of the Environment of Japan initially estimated that the tsunami produced some 25 million tonnes of debris, which included both material that remained on land and material that was transported out to sea (NOAA 2012a). The most recent estimate from the Government of Japan (GoJ) is that the tsunami swept

Figure 1 (top) Photograph of a small cluster of Japan tsunami marine debris taken by the U.S. Navy close to the coast of Japan on 13 March 2011, two days after the tsunami. The varied nature of the debris is evident in this image. Clusters of debris such as this have now dispersed over large expanses of the ocean. (bottom) Filament of tsunami debris being transported offshore on 14 March 2011. The dominance of lumber gives the floating debris its orange-brown colour.

approximately 4.8 million tonnes of debris into the ocean, of which 70% consisted of the heavier objects that sank to the bottom within a relatively short distance of the coast of Japan. It is thought that a remaining mass of debris, with an estimated weight of about 1.5 million tonnes $1.5\times10^{9}\,\mathrm{kg}$, is presently afloat in the North Pacific Ocean.

While the composition of the floating debris not known in great detail, it is estimated that the preponderance of the debris consists of construction materials that come from the houses that were swept out to sea (GoJ 2012a). It is also understood that the debris includes many floating objects such as containers, vessels ranging in size from small boats to medium-size ships, along with nets and floats used in the aquaculture industry. Much of these lighter materials, including objects made of plastic, wood, metal containers, and fishing gear (nets, lines, buoys, etc.), can be expected to remain afloat at or close to the surface for a long period of time. Larger

objects, such as houses, are expected to break up with time into many smaller pieces. Due to the construction of Japanese housing, this implies that lumber is likely an important component of the tsunami debris (e.g., Figure 1). Over a period of several years, lumber will become water-logged and eventually sink to the bottom. Other light objects, particularly those made of plastic, can stay afloat virtually indefinitely. Such objects can have 'windage' such that they are subject to direct forcing by wind near the sea surface.

The Tōhoku tsunami inundated the Fukushima nuclear power plant, damaging reactors and stored spent fuel rods, and subsequently leading to leaks of radioactive material, specifically iodine-131 (^{131}I, half-life 8.02 days) and cesium-137 (^{137}Cs, half-life 30.17 years) into the atmosphere and ocean. The discharge of radioactive water into the ocean occurred well after the vast bulk of the debris had been transported seaward by the ocean currents. Plumes of radioactive material escaped from the reactors into the atmosphere shortly after the tsunami, and some of this material may have been deposited onto floating debris. Since ^{131}I has a short-half life and ^{137}Cs is water soluble, radioactivity deposited on the debris is likely to either have degraded below detection limits or have washed off during the prolonged exposure in the ocean. Given these considerations, there is only a remote possibility that the marine debris is contaminated by radioactive materials (NOAA 2012a).

Transport and dispersal by ocean currents and winds

Marine debris is subject to transport and dispersal by ocean currents and by oceanic winds and their attendant waves. Large-scale ocean currents and winds are responsible for transport over large distances. The ocean is also a very turbulent environment, and smaller scale motions and eddies will gradually disperse an initially compact debris cluster into a diffuse cloud of objects that is spread over a large area.

The Tōhoku tsunami deposited debris into the ocean along the northern coast of Honshu Island. The Oyashio and Kuroshio Currents merge together in this region to form the Kuroshio Extension, a swift eastward-flowing current which will have carried some of the debris away from the coast of Japan towards the central North Pacific (see Figure 2). In the central North Pacific, the flow becomes very broad and sluggish and is referred to as the North Pacific Current (or the West Wind Drift). It is expected that marine debris from the Tōhoku tsunami has been and will continue to be transported by this relatively slow moving current system across the Pacific Ocean towards the west coast of North America.

Near the North American coast, the North Pacific Current splits (bifurcates) into northeastward and southeastward flowing current systems, referred to as the Alaska Current and California Current, respectively. It is expected that the tsunami debris will be transported into both of these current systems as it approaches North America. Debris flowing northward into the Alaska Current is more likely to enter Canadian waters, while debris transported in the southward flowing branch is more likely to impact the U.S. west coast and Hawaii.

Studies of the motion of near-surface drifters have found that the latitude of bifurcation is about 50°N (Bograd et al. 1999), although there is some year-to-year variability in this latitude. To reach the British Columbia shoreline, debris must traverse a region of variable flow located eastward of the bifurcation zone. Here generally westerly winds will drive segments of the debris field onto the coast. Currents can only bring debris close to the shore. Debris is then deposited on the shoreline by the action of retreating tides, onshore winds, and waves.

During summer, winds along much of the B.C. coast are generally from the north, leading to upwelling and offshore transport of surface waters. This offshore transport will help to protect the coast, and the deposition of debris is less likely to occur during the summer upwelling season. The winds reverse during winter and are generally from the south. This creates

downwelling conditions and onshore transport of surface waters which favours deposition of debris along the coast.

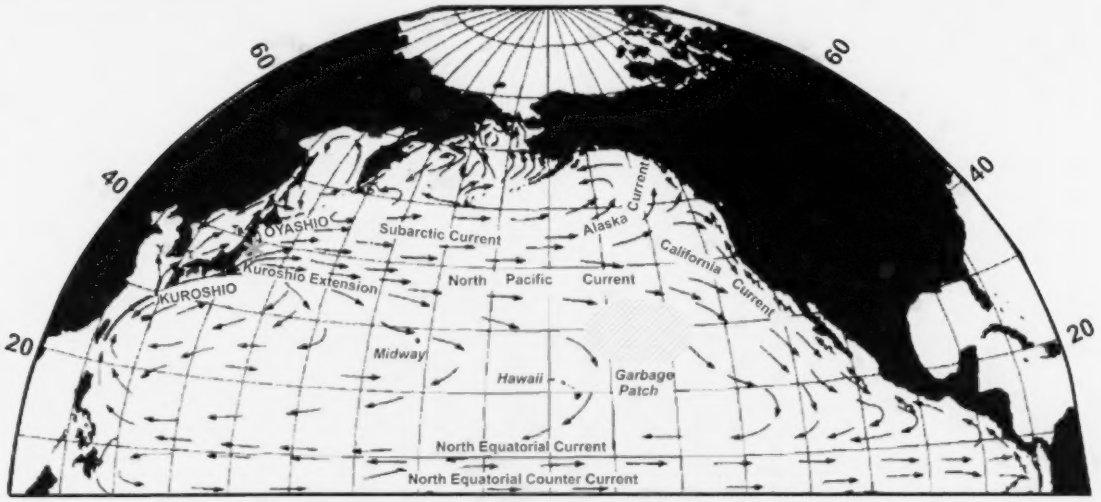


Figure 2. Schematic diagram showing major currents of the North Pacific. The red symbol indicates the approximate location where debris generated by March 2011 tsunami entered the ocean. The hatched blue area indicates the approximate location of the "North Pacific Garbage Patch". Adapted from Figure 3 in Tabata (1975).

The major currents depicted in Figure 2 represent an idealized view of the large-scale circulation in the North Pacific. Highly variable, energetic motions occurring over a range of smaller scales are also present at any given time. These eddy motions are ocean analogues to the atmospheric systems that produce familiar day-to-day weather patterns. The main effect of eddy variability on the marine debris is to spread the debris out over an increasingly large area. For example, consider the following estimate of dispersion in which the length scale of dispersion of a cluster is

$$d = \sqrt{2Kt} \ ,$$

where t is the elapsed time and K is the lateral eddy diffusivity based on single particle dispersion. Zhurbas and Oh (2003) reported that values of 5,000 - 10,000 $m^2\ s^{-1}$ are representative of single particle diffusivity within the Kuroshio Extension. Taking a value at the lower end of the diffusivity range results in a dispersion scale of $d \approx 400$ km after 6 months. A circle with a radius of 400 km encompasses an area of about 500,000 km^2, which is comparable to the area of the province of Alberta (660,000 km^2) or the state of California (424,000 km^2). Thus, based on this simple calculation, the tsunami debris is likely to have been dispersed into a very diffuse cloud that extends over hundreds of thousands of square kilometres after only 6 months. Within this large expanse, the debris is not expected to be uniformly distributed. Rather patchy clumps and elongated filaments of debris are likely to be observed.

The tsunami debris includes objects that have significant windage. This refers to objects that float appreciably above the water line and are subject to direct forcing by winds near the sea surface. Typically, large floating objects, such as floats, drums, buoys, containers, docks and vessels (including those that are partially submerged), have significant windage. The extent to which the tsunami debris is composed of high windage objects is uncertain. However, the likelihood is that such objects represent a relatively small fraction of all the debris. Nevertheless,

this may belie their overall importance, since, in many instances, large, potentially hazardous, objects will have significant windage.

The velocity of objects with windage, $\mathbf{U}$, can be considered as the sum of two components, $\mathbf{U} = \mathbf{U}_{water} + \mathbf{U}_{wind}$, where $\mathbf{U}_{water}$ is the horizontal velocity of the water at the ocean surface and $\mathbf{U}_{wind}$ is the velocity of the object relative to the water. This component arises from the direct forcing of the object by the wind blowing over the sea surface. Based on a balance of wind and ocean drag forces, a simple model of the wind-driven component of velocity of an object is (GoJ 2012b)

$$\mathbf{U}_{wind} = k\sqrt{\frac{A}{B}}\mathbf{U}_{10}$$

where $\mathbf{U}_{10}$ is the velocity of the wind at 10 metres above the sea surface, A and B refer the surface area of the object above and below the water line, respectively, and $k \approx 0.025$ is a constant. Thus, according to this relation, an object with, for example, equal surface area above and below the water line $A/B = 1$ will drift relative to the water at a rate of 2.5% of the 10-metre wind speed. This drift is in the direction of the wind, which may be aligned somewhat differently than the direction of the surface current. Generally, objects with significant windage will be transported across the ocean more rapidly than zero-windage objects. The influence of windage in model simulations of debris transport is discussed below.

Observations and present status

Offshore transport of the tsunami debris was observed very soon after deposition into the ocean. The debris was tracked for a short time by the NESDIS environmental monitoring satellite (NOAA 2012b), and patches of debris could be seen in satellite imagery for about a month following the tsunami. However, by 14 April 2011 the cloud of debris had dispersed to the point that it ceased to be visible in the satellite imagery (NOAA 2012b). Since this time there have been a number of efforts to use higher resolution satellite imagery to observe the tsunami debris. In December 2011, researchers at the United States National Oceanic and Atmospheric Administration (NOAA) examined high resolution satellite imagery of a 50 km by 60 km patch of ocean where model simulations suggested debris would be located. This effort failed to detect any debris, leading to the conclusion that either the scale of the debris was smaller than the 1–2 metre resolution of the satellite imagery, and/or that the debris was not in the forecasted location. Subsequent efforts along these lines are ongoing but have yet to yield definitive results. Overall, this work underscores the limits of our knowledge regarding the tsunami debris. The inability to monitor the transport of the debris by satellite means that comprehensive observations are lacking. As such, the overall distribution of the tsunami debris in the ocean is unobservable and effectively unknown at this time.

Figure 3. (Top) Photograph of the Ryou-Un Maru taken by the Canadian Coast Guard on March 20, 2012 about 200 km west of Haida Gwaii, British Columbia. (Bottom) Concrete dock from Japan on Agate Beach, Oregon, June, 2012.

The GoJ has compiled and catalogued direct observations of tsunami debris at sea based on areal observations and sightings from commercial vessels (GoJ 2012c). This record consists of some 97 sightings from April 2011 through November 2011. All of these sightings were from a sector of the Pacific that is west of the dateline and south of 45N. Most of the sightings were of larger objects such as small vessels and containers. Many of the observed vessels were reported to be either capsized or partially submerged. The last of these reported sightings occurred in November, 2011.

NOAA is presently compiling reports of suspected tsunami debris observed both at sea and along shorelines, including the coast of British Columbia. As of 18 October 2012, NOAA has received a total 1385 reports of tsunami debris sightings with 620 shoreline sightings, and 765 at-sea sightings. Reports of tsunami debris have originated from along the coasts of B.C., Alaska, Washington, Oregon, California and Hawaii. A graphical display of the geographical distribution of the reported debris sighting is available online and updated regularly (NOAA 2012c). The distribution debris in these reports is likely more representative of the frequency of

human passage rather than the actual distribution of the tsunami debris. Of all these sightings, to date only 14 objects have been definitively confirmed to originate from the Tohoku tsunami. It is certainly plausible that many of the other objects reported to NOAA also originated from the tsunami. It is also likely that many do not, as marine debris is a common and widespread phenomenon.

One of the first reports of confirmed tsunami debris came from the *STS Pallada*, a Russian sailing vessel that was travelling west across the Pacific to Vladivostok (IPRC 2011a). As it was heading past Midway Atoll, the crew of the *Pallada* noticed many floating objects in the water. On 22 September 2011, about 800 km northwest of Midway Atoll, the *Pallada* encountered a small fishing boat, registered in Fukushima, Japan. Much as expected, tests of the boat found that radiation levels were below detection limits. Observations of additional debris were made from the *Pallada* as it continued on a north-westward course towards Japan.

During the first half of 2012, a few very large pieces of Japan tsunami debris arrived along the west coast of North America. This includes the *Ryou-Un Maru*, the 50-metre 'ghost ship', that was discovered in Canadian waters, about 200 km off the coast of Haida Gwaii on 20 March 2012 (see Figure 3). Subsequently, on 18 April 2012, a shipping container carrying a motorcycle was discovered washed up on the northeastern shores of Haida Gwaii near Rose Spit, B.C.. Another notable example of confirmed tsunami debris is the large concrete dock that washed up Agate Beach about 1.5 km north of Newport, Oregon on 5 June 2012 (Figure 3). Each of these objects, along with others suspected but not confirmed to be Japan tsunami marine debris, have significant windage. It is believed that this has played an important role in their early arrival at the coast. As emphasized above, there has been no monitoring of the movement of even large pieces of debris, so there was no advanced warning of the arrival of these objects at the coast. The large dock shown in Figure 3, for example, was first reported floating offshore only the day prior to its beaching on the Oregon coast (Oregon Parks and Recreation Department, 2012).

Model simulations of debris distribution

Since direct satellite observations of the tsunami debris are unavailable after April 2011, it is necessary to rely on models to estimate the present distribution of the debris and to forecast its distribution in the future. While models may be useful in this regard, the extent to which they can accurately simulate the transport of the tsunami debris is an open question. A major source of uncertainty is that the windage of the debris is not well established. As indicated below, model simulations indicate that the windage of an object has a pronounced influence on the rate at which it is transported across the Pacific, and also on its direction of travel.

Results from representative model simulation are now briefly described. Attention is given first to a model based on climatological drifter statistics. This model allows integrations well into the future and may be helpful to understand the long-term fate of the debris. This simulation is limited, however, to debris with essentially zero windage. Secondly, results are shown from a model that is based on the actual winds over the ocean since March 2011, and which allows for the effects of various degrees of windage. Simulations of this type can provide an estimate of the distribution of debris with different windages. They may also be helpful in understanding the limited observations of tsunami debris that have been made to date.

Climatological forecast

Long-term forecasts of the transport of tsunami debris were conducted at the University of Hawaii (IPRC 2012b) and by NOAA (NOAA 2012a). Results from these simulations, which were based on differently formulated models, are generally consistent which each other. Figure 4 shows the distribution of the tsunami debris at different times as predicted by the University of

Hawaii model. This is a statistical model is based on the trajectories of a large number of drifters that were deployed in the ocean over a 30-year time period (Maximenko et al. 2012). These trajectories are representative of the motion of objects that move with the top layer of the water column. Accordingly, they apply to the motion of objects that float mostly below the water line and have effectively zero windage. The simulation is not, however, representative of the motion of higher windage objects that float well above the water surface and are exposed directly to wind forcing.

The following are some of the salient results from this simulation.

- As anticipated, the simulation shows dispersion of the debris over a large area as it is being transported across the Pacific toward the west coast of North America.
- The leading edge of the debris cloud is predicted to reach the North American continent about 2 to 2.5 years after deposition into the ocean. Based on this prediction, low windage debris can be expected to start arriving along the west coast of North America during the first half of 2013.
- Following its initial appearance, the rate at which such debris arrives along the coast should increase gradually. Low windage tsunami debris will continue to be transported by ocean currents close to the coast for a number of years, and it is possible that such debris will continue to be deposited along the British Columbia shoreline during this time.
- In the simulation, most of the debris is transported south into the California Current system, with a smaller amount entering the Alaska Current. Debris caught in the California Current will be transported away from the coast of British Columbia, but may wash up along the U.S. west coast or be transported eventually to the Hawaiian Islands
- The simulation shows most of the low windage debris (> 90%) remaining in the ocean after 5 years. In particular, the simulation shows a large fraction of the debris accumulating within the Sub-tropical Convergence Zone (Figure 1). This is a large expanse of ocean northeast of Hawaii, referred to as the North Pacific Garbage Patch, where floating debris, especially plastics, has accumulated over time due to the convergence of surface wind-driven currents (Maximenko et al. 2012). The simulation shows debris remaining trapped within the Garbage Patch for many years.

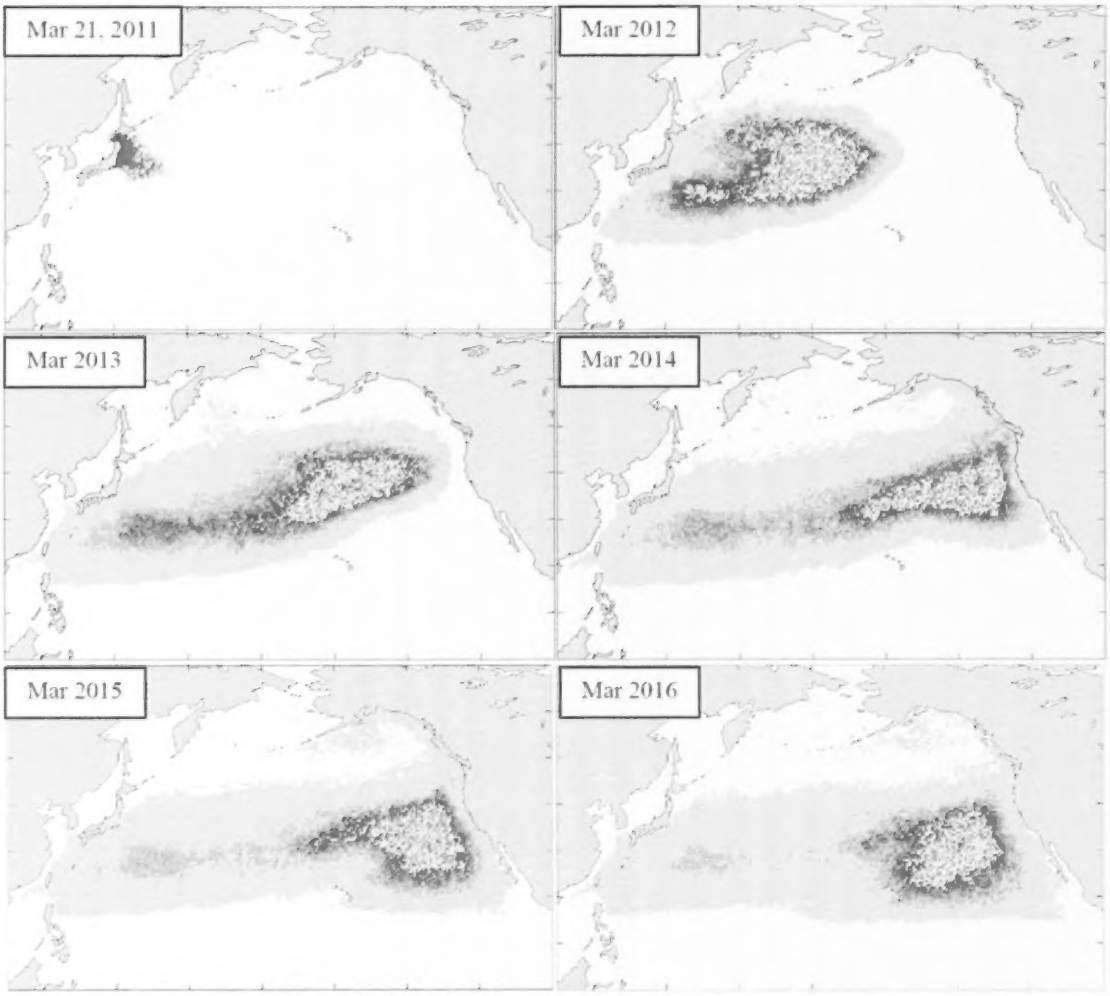


Figure 4. Distribution of the tsunami debris at yearly intervals from the climatological model of N. Maximenko and J. Hafner of the University of Hawaii. These results apply to debris with effectively zero windage. In the simulation, debris found in proximity to the coast of British Columbia peaks by about March 2014, some three years after its release into the ocean. Debris remains present along the British Columbia coast for at least five years, albeit at reduced levels. This figure is drawn from (IPRC 2012b).

Influence of windage

Recent model simulations have made use of the actual observed winds over the Pacific since March 2011 to simulate the movement of the debris. This is significant since there can be important year-to-year variations in the winds at large-scales over the North Pacific. In addition, these simulations have considered the influence of various degrees of windage on the transport of debris. Results from a number of such models are now available, including those from NOAA (2012d) and those produced by the GoJ (2012d). Figure 5 shows results at two different times from new simulations conducted at the University of Hawaii by N. Maximenko and J. Hafner.

Debris with varying degrees of windage is represented in the simulation as a relative concentration (equivalent to the number of pieces of debris per unit area of ocean). This

simulation makes use of observed winds and altimeter data to estimate time-varying ocean currents. While the results are illustrative of the behaviour of objects with different windages, they do not represent a simulation of the distribution of debris in the ocean. As discussed below, producing a 'nowcast' of the debris distribution requires making assumptions regarding the partition of windage among the pieces of debris, which is unknown.

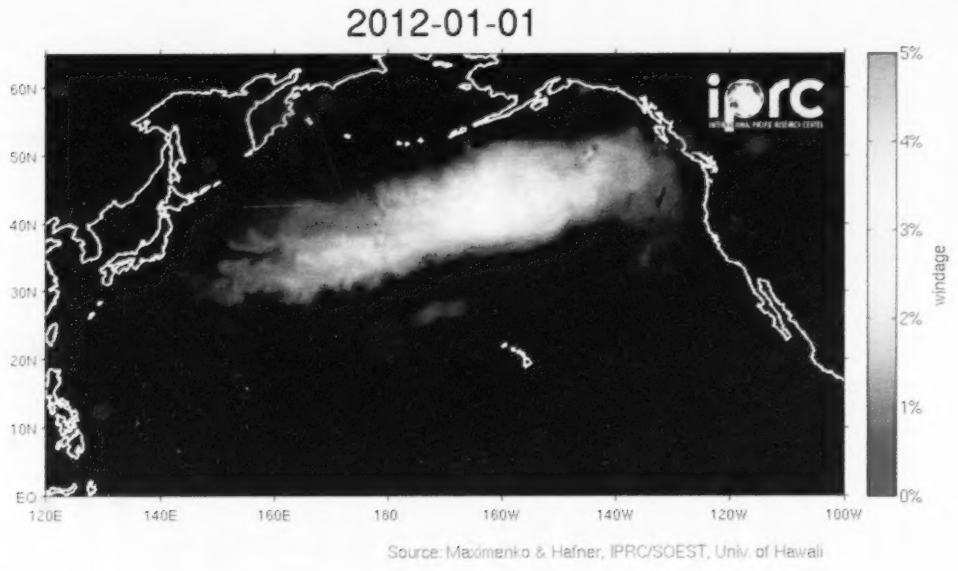
It is evident from the results of Figure 5 that windage has a marked influence on the rate at which tsunami debris traverses the Pacific. Simulated debris with very high windage (4 - 5%) arrives at, or close to, the west coast of N. America during the winter of 2011-2012, roughly 9 months to one year after being released into the ocean. Moreover, such debris, driven by the prevailing westerly winds, tends to migrate further north than the zero windage debris depicted in Figure 4. By spring of 2012 the simulation shows that debris with appreciable windage has either already washed ashore, or is located in proximity of the coasts of Alaska, B.C, Washington and Oregon.

These model results are consistent with the observed arrival at the coast of high windage tsunami debris during the first half of 2012. This applies, in particular, to the large objects mentioned above, such as the container discovered on the shores of Haida Gwaii and the 'ghost ship' that was found offshore of Haida Gwaii. The latter was estimated to have a windage of about 3.5% (G. Watabayashi, NOAA, pers. comm.).

The results of figure 5 also show that, by April 2012, debris with zero to moderate windage (≤ 2%), which is likely representative of the most of the tsunami debris, located well offshore and further to the south than higher windage debris. The distribution of the zero windage debris is generally consistent with the climatological forecast discussed above. In particular, the simulation shows a very widely dispersed debris cloud with the greatest debris density is located northwest of Hawaii, centred about the 40°N latitude.

In the simulation, the leading edge of debris with moderate (~2%) windage approaches the west coast of N. America during spring to summer of 2012. Under action of the prevailing summer winds, the simulation shows this moderate windage debris tending to veer to the south, transporting it away from the BC coast. As it veers to the south, this debris tends to drift away from the coast of North America, and by September 2012 much of it is spread over a large area between California and Hawaii. The trade winds will cause this debris to continue drifting to the west during the winter of 2012-13, towards Hawaii and subsequently back towards Asia.

The results on windage that are illustrated in Figure 5 point to the difficulty in constructing a comprehensive picture of the present geographical distribution of tsunami debris in the ocean. The construction of a 'nowcast' of the tsunami debris would require the assumption of some distribution of windage among the pieces of debris. The difficulty is that the windage of the debris is largely unknown and can only be guessed at. It is unclear, for example, what fraction of the tsunami debris has 3 - 4% windage, what fraction 2%, and so forth. Yet, the results of a 'nowcast' of the tsunami debris would depend sensitively on this assumed distribution. For this reason, it is difficult to provide a meaningful estimate of the rate at which of debris will approach the coastline of British Columbia, or the quantity of debris likely to be washed ashore.



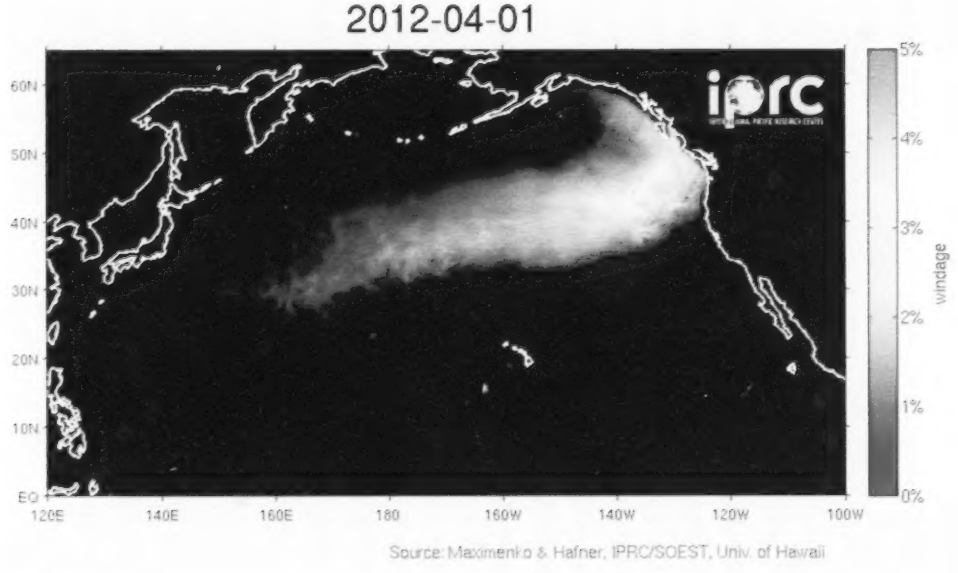
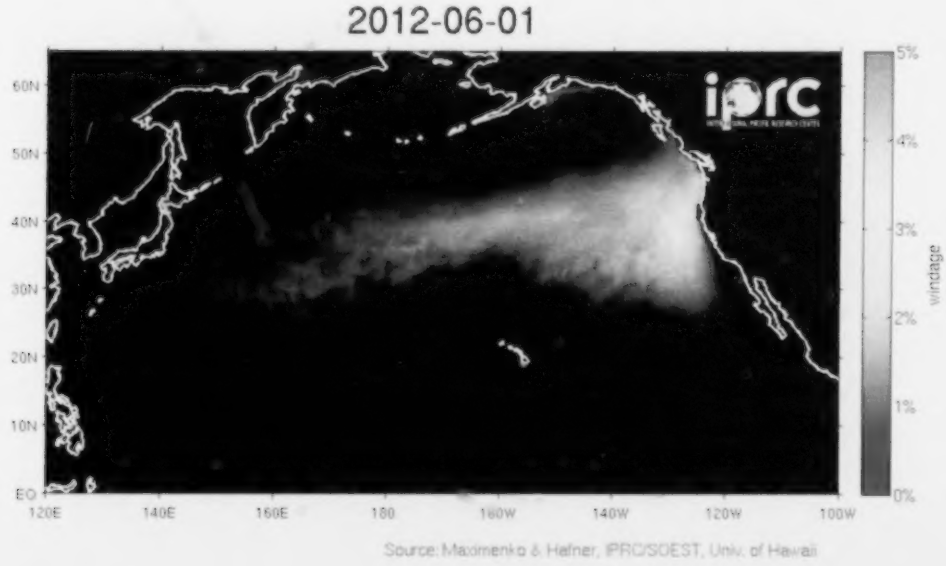


Figure 5. Results from model simulations of debris with varying (0-5%) windage. Initially, similar amounts of virtual debris with different windages are released at the coast of Japan. This debris is subsequently transported by ocean currents and driven by time-dependent winds. The calculation illustrates the behaviour of objects with different windage under realistic wind forcing. Panels are shown above for 1 January 2012, and 1 April 2012. It should be kept in mind that these results are merely illustrative of the influence of windage on the transport of debris. The actual tsunami debris deposited into the ocean did not contain similar amounts of debris at different windages. Rather it likely had greater amounts of low to moderate (0-2%) windage debris.



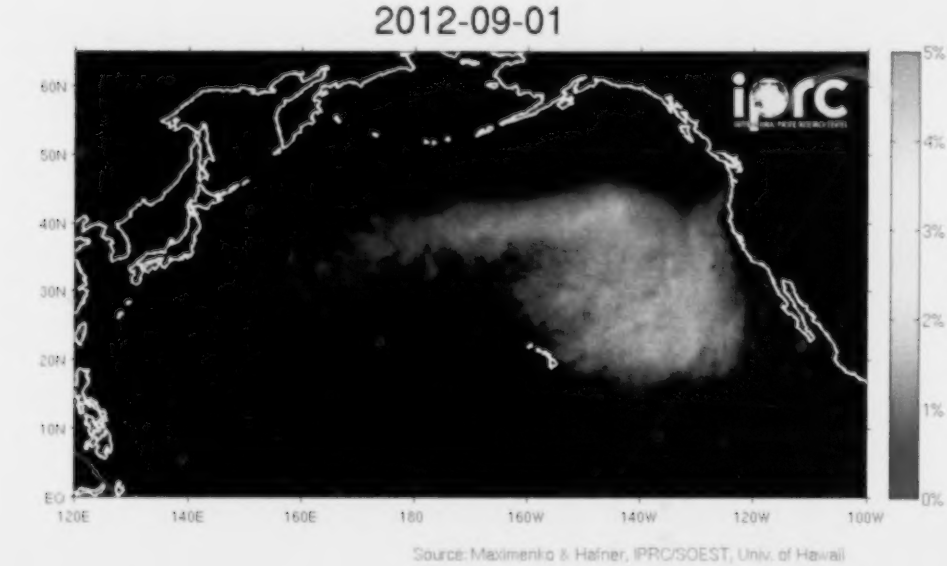


Figure 5 (continued). Results from a model simulation of debris with varying levels of windage for 1 June 2012 and 1 September 2012. In the simulation, most of the very high windage (4-5%) debris has washed ashore by early summer. With the establishment of summer wind conditions, the simulation shows debris with moderate windage being displaced to the south and then away from the coast of North America. In the simulation, debris with very low windage is widely dispersed across the central North Pacific by early Sept. 2012.

Environmental impacts and hazards to navigation

The potential environmental impacts of the tsunami debris on the coastal waters and shoreline of British Columbia are difficult to ascertain with confidence. Presently, the volume of debris likely to reach the coast cannot be estimated, and the composition of the debris is poorly known. Consequently, the extent of the risk to habitat, species and ecosystems presented by the tsunami debris cannot be stated with confidence at this time. One potential risk is that of invasive species. The dock that washed up on the Oregon coast, for example, is known to have carried more than 90 non-native species to the Oregon water, including *Undaria pinnatifida*, an invasive type of marine algae (Oregon Parks and Recreation Department, 2012).

Likewise, the possible hazards to navigation presented by the debris are difficult to determine. There may be a few large objects amidst the debris that arrives in British Columbia waters (e.g., containers from shipping), and there is at least a hypothetical risk of collision at sea. In addition, the debris may present a risk of entanglement in floating fishing gear, ropes and nets, but the magnitude of this risk is unknown relative to pre-existing risks which are poorly documented.

Conclusions

While many interesting and important questions can be posed regarding the marine debris produced by the Tōhoku tsunami, only tentative answers can be given, amid much uncertainty. What is known is that a large mass of debris was swept into the Pacific Ocean along the coast of Japan. The Government of Japan estimates that about 70% of the debris swept into the ocean sank on the continental shelf of Japan, and that roughly 1.5 million tonnes of debris remains afloat in the North Pacific Ocean (GoJ 2012a). The composition of this debris field is not known in detail, but it is thought that perhaps the most important source of debris is the houses that were swept to sea from coastal towns in Japan. As such, lumber is likely to be an important constituent of the debris field.

Shortly after deposition into the ocean, the debris was transported offshore by ocean currents. Satellite tracking of the debris was possible for about one month, up to mid-April 2011 after which time the debris field was too widely dispersed to be resolved in the satellite imagery. Since this time there has been no satellite tracking of the tsunami debris, and its distribution in the ocean is not known. Presently, the debris field is likely to be highly diffuse, with debris dispersed over a vast expanse of ocean. Since there is no tracking of the tsunami debris by satellite, reliable data on the location, pathways and drift rates of tsunami debris in the North Pacific Ocean are currently lacking.

Ocean currents and prevailing winds are expected to transport tsunami debris across the Pacific to the west coast of North America. There is supporting evidence for this view from the observations of debris made west of the dateline by the Government of Japan up to November 2011, and by opportunistic sightings at sea that have been compiled and catalogued by NOAA. A few major pieces of debris arrived along the west coast of North America during the first half of 2012. Items confirmed to originate from the tsunami have been found on the shores of Alaska, British Columbia, Washington State, Oregon and Hawaii, indicating that the tsunami debris is now widely dispersed.

Estimates of the present distribution of the tsunami debris, along with projections for the future must depend on the use of models. There is much uncertainly in this regard as such models have not been adequately tested. Moreover, the results of models simulations show considerable sensitivity to the windage of the debris, which is poorly known. In particular, the rate of transport across the ocean, along with the trajectory that debris follows, depends sensitively on assumptions made regarding the windage of the debris. Overall, much of the

debris may have relatively low windage, particularly if it is assumed that construction materials and lumber are the most important component of the debris. Model simulations show that debris with essentially zero windage will begin to arrive along the west coast of North America during the first half of 2013. Most of this debris is forecast to move south with the California Current once it reaches North America. Some of this load may wash ashore along the coasts of Washington, Oregon, and possibly California before moving towards the Hawaiian Islands. A smaller portion of the debris is forecast to be transported north into the Alaska Current, and it is from this load that low windage debris is most likely to wash ashore in British Columbia, as well as in Alaska. This debris could impact the B.C. coastline for a number of years. The review of Miller and Brennan (2012) considered the transport of tsunami debris to the coast of Washington State, and similarly estimated that landfall of debris would be spread over a period of a few years. The models also show the great bulk of low windage tsunami debris remaining in the ocean for many years and collecting in the North Pacific Garbage Patch.

Debris with significant windage is transported more quickly across the North Pacific. Model simulations show that such debris reaches the coast of North America during the winter of 2011-2012. This is consistent with the appearance of high windage debris along the west coast of North America in early 2012, roughly one year after the tsunami. Models also indicate that during this first year, high windage debris tends to follow a more northerly course than does low windage debris. This indicates the coast of British Columbia receiving considerable amounts of relatively high windage debris. Although such debris may not represent a large fraction of the total debris load, it is nevertheless potentially significant since very large objects that are potentially hazardous to navigation tend to have appreciable windage. This includes objects such as the container that beached on the shores of Haida Gwaii in April 2012, and the 'ghost ship' discovered off Haida Gwaii on 20 March 2012.

It is important to note that marine debris from a variety of domestic and foreign sources floats into Canadian waters and is deposited on British Columbia shorelines every day and that most of this debris consists small pieces with no markings that would link it to the tsunami. The models used to forecast debris movement are not sufficiently accurate to identify specific shoreline locations in British Columbia of tsunami debris deposition. However, existing patterns of marine debris deposition on shorelines are not expected to change greatly. Therefore, shorelines that receive debris at present (e.g., collector beaches), particularly those found along the west coast and around Haida Gwaii are also likely to receive tsunami debris. Due to patterns of ocean currents, it is considered unlikely that there will be much tsunami debris entering within the Strait of Georgia.

Although the March 2011 tsunami was probably one of the largest single-source loadings of marine debris to the North Pacific Ocean, the significance of this addition is uncertain because the existing load of marine debris is not well quantified. Shoreline monitoring has been conducted for several years in the Olympic Coast National Marine Sanctuary of Washington using a well documented protocol established by the NOAA Marine Debris Program (http://marinedebris.noaa.gov/). While British Columbia has not had a systematic shoreline monitoring program, some baseline information on debris may be available from annual beach clean-up days coordinated by environmental non-governmental organizations. Follow-up work is needed to assess the quality of these data.

In spite of these deficiencies, some perspective on the load represented by the tsunami debris may be gained via a simple calculation along the lines of those given in Miller and Brennan (2012). They estimate that between 2% and 25% of the tsunami debris will be washed ashore over a period of a few years following the tsunami. The lower bound of 2% is based on the observed recovery rate of a large number of running shoes and plastic toys accidentally released into the ocean (Ebbesmeyer and Ingraham, 1994). We now calculate the debris load

assuming uniform deposition along the 15,000 km length of the 'general sea coast' of North America from the Aleutian Islands to the Baja peninsula. This value for the length of the sea coast neglects small scale coastal irregularities such as fjords or embayments. Distributing 2% - 25% of the estimated 1.5 million tonnes of debris uniformly along this length of coastline gives 2 - 25 tonnes of debris per kilometre. For comparison, Miller and Brennan (2012) report baseline deposition of marine debris on the shores of the state of Washington occurs at a rate of about 0.7 tonnes per km per year. Uniform deposition along the coast is, of course, an extreme idealization of the actual deposition that will occur of the tsunami debris. Nevertheless, this calculation serves to illustrate that the tsunami debris has the potential to increase significantly the load of marine debris deposited on the west coast of North America for a number of years. It also points to the very wide uncertainty inherent in constructing any such estimate.

Neither the existing risks to habitats, species and ecosystems in British Columbia from marine debris nor the incremental increase in risks associated with the arrival of tsunami debris are quantifiable because existing risk from marine debris loads in Canadian waters are poorly understood and documented. Although there may be an increased risk to species in British Columbia associated with entanglement in drifting nets, ropes, and the consumption of plastics, the magnitude of this increase relative to the pre-existing risks from marine debris is unknown. Also uncertain is the magnitude of risk that large pieces of tsunami debris might be a vector for the spread of invasive species.

The risks from radioactivity associated with ^{131}I and ^{137}Cs on the debris originating from the Fukushima nuclear power plant are believed to be very low. ^{131}I has a half-life of about 8-days and activity levels on debris would now be well below the most sensitive detection limits and any known effect threshold. ^{137}Cs salts are water-soluble and can be washed off debris during prolonged exposure while at sea. Testing of tsunami debris collected by a Russian research vessel in September 2011 found that radioactivity levels were below detection limits. There is some potential for bioaccumulation of ^{137}Cs in aquatic food webs, but the risk to marine species and ecosystems in British Columbia through biological transport is likely low because ^{137}Cs is rapidly eliminated from organisms, resulting in a short biological half-life of 2-3 months.

Baseline navigational impacts in Canadian waters associated with marine debris are poorly known and, therefore, the additional impacts associated with tsunami debris arriving in Canadian waters cannot be quantified at present. The greatest risk to navigation is likely related to large objects (e.g., shipping containers, floating or partially submerged vessels, etc.) arriving in coastal waters and shipping lanes. The probability of houses surviving a trans-Pacific crossing intact is believed to be very low, and the number of large objects deposited in the sea off the coast of Japan that remain afloat may not have been high. Drifting nets and ropes and other entangling debris from the tsunami may incrementally increase the current risk of navigational impacts associated with entangling debris in Canadian waters. Small objects (e.g., logs or small pieces of wood) are not believed to pose an additional risk to vessel traffic off the west coast of Vancouver Island. Tsunami debris, when it arrives, is unlikely to pose a risk to navigation in the Strait of Georgia since near-surface current patterns will ensure that little, if any, debris enters this area.

Contributors

Name	Affiliation
Cummins, Patrick	DFO, Science
Thomson, Richard	DFO, Science
Freeland, Howard	DFO, Science

Approved by:

Robin Brown
Manager, Ocean Sciences Division
DFO Science, Pacific Region
Sidney, British Columbia

Notes and Sources of information

Bograd, S., R.E. Thomson, A.B. Rabinovich, and P.H. LeBlond. 1999. Near-surface circulation for the northeast Pacific Ocean from WOCE-SVP satellite-tracked drifters. Deep-Sea Res. II, 46: 2371-2403.

Ebbesmeyer, C., J.W. Ingraham Jr. 1994. Pacific toy spill fuels ocean current pathways research. EOS, Transactions, American Geophysical Union, 75, 425-432.

Government of Japan (GoJ). 2012a
http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu/souryou_eng.pdf

Government of Japan (GoJ). 2012b.
http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu/souryou/Trajectory_01.pdf

Government of Japan (GoJ). 2012c. http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu_eng.html

Government of Japan (GoJ). 2012d.
http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu/souryou/Trajectory_03.pdf

International Pacific Research Center (IPRC). 2012a. Russian ship finds tsunami debris where scientists predicted. Joint Press Release with the *STS Pallada*. Available at: http://iprc.soest.hawaii.edu/news/press_releases/2011/pallada_tsunami_debris.pdf. IPRC, School of Ocean and Earth Science and Technology (SOEST), University of Hawai'i at Mānoa

International Pacific Research Center (IPRC). 2012b. Where will the debris from Japan's tsunami drift in the Ocean? Joint press release with the STS Pallada. Available at: http://www.soest.hawaii.edu/iprc/news/press_releases/2011/maximenko_tsunami_debris.pdf. IPRC, School of Ocean and Earth Science and Technology (SOEST), University of Hawai'i at Mānoa.

Maximenko, N., J. Hafner, and P. Niiler. 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar. Pollut. Bull. 65: 51-62.

Miller, I., J., Brennan. 2012. Debris accumulation scenarios in Washing State from the March 2011 Tohoku tsunami. Washington Sea Grant. WSG-TR 12-02.

NOAA 2012a. http://marinedebris.noaa.gov/info/japanfaqs.html

NOAA 2012b. http://www.nesdis.noaa.gov/AboutNESDIS.html

NOAA 2012c. http://marinedebris.noaa.gov/info/images/erma.jpg

NOAA 2012d. http://marinedebris.noaa.gov/info/images/gnomegraphic.jpg

Oregon Parks and Recreation Department 2012.
http://www.oregon.gov/OPRD/PARKS/agatebeach_dock.shtml

Tabata, S. 1975. The general circulation of the Pacific Ocean and a brief account of the oceanographic structure of the North Pacific Ocean. Part I – circulation and volume transports. Atmosphere 13: 133-168.

Zhurbas, V. and I.S. Oh. 2003. Lateral diffusivity and Lagrangian scales in the Pacific Ocean as derived from drifter data. J. Geophys. Res. 108(C5): 3141, doi:10.1029/2002JC002241.

This Report is Available from the:

Center for Science Advice (CSA)
Pacific Region
Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, British Columbia
Canada, V9T 6N7

Telephone: 250-756-7208
E-Mail: CSAP@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs

ISSN 1919-3750 (Print)
ISSN 1919-3769 (Online)
© Her Majesty the Queen in Right of Canada, 2013

La version française est disponible à l'adresse ci-dessus.

Correct Citation for this Publication:

DFO. 2013. Transport of Japan tsunami marine debris to the coast of British Columbia: An updated review. DFO Can. Sci. Advis. Sec. Sci. Resp. 2012/045.